Geochemical evaluation of observed changes in volcanic activity during the 2007 eruption at Stromboli (Italy)

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Abstract

On February 27, 2007 a new eruption started at Stromboli that lasted until April 2 and included a paroxysmal explosion on March 15. Geochemical monitoring carried out over several years revealed some appreciable variations that preceded both the eruption onset and the explosion. The carbon dioxide (CO_2) flux from the soil at Pizzo Sopra La Fossa increased markedly a few days before the eruption onset, and continued during lava effusion to reach its maximum value (at 90,000 g $m^{-2}d^{-1}$) a few days before the paroxysm. Almost contemporarily, the $\delta^{13}C_{CO2}$ of the SC5 fumarole located in the summit area increased markedly, peaking just before the explosion ($\delta^{13}C_{CO2}$~-1.8‰). Following the paroxysm, helium (He) isotopes measured in the gases dissolved in the basal thermal aquifer sharply increased. Almost contemporarily, the automatic station of CO_2 flux recorded an anomalous degassing rate. Also temperatures and the vertical thermal gradient, which had been measured since November 2006 in the soil at Pizzo Sopra La Fossa, showed appreciable variabilities that lasted until the end of the eruption. The geochemical variations indicated the degassing of a new batch of volatile-rich magma that preceded and probably fed the paroxysm. The anomalous $^3He/^4He$ ratio suggested that the ascent of a second batch of volatile-rich magma toward the surface was probably responsible of the resumption of the ordinary activity. A comparison with the geochemical variations observed during the 2002–2003 eruption indicated that the 2007 eruption was less energetic.

Keywords: geochemistry, eruption, dissolved gases, Stromboli, volcanic activity.

1. Introduction

Stromboli, the northernmost island of the Aeolian arc in the southern Tyrrhenian Sea, represents the subaerial part of a large edifice extending from depths of about 2500 to 924 m a.s.l. It is typically characterized by persistent mildly explosive activity (referred to as "Strombolian activity") that probably began between the third and the seventh century AD and continued without significant interruptions or modifications until the present time (Rosi et al., 2000). This normal activity is episodically interrupted by lava effusions and more violent explosions, called "major explosions" and "paroxysms" (Barberi et al., 1993). Paroxysms are the most powerful explosive events of Stromboli. They occur every 5–15 years with a duration of hours to a few days, and can affect the inhabited areas of the island (Stromboli and Ginostra villages) by the fallout of bombs and blocks, ash showers, glowing avalanches, and tsunamis (Rittmann, 1931; Barberi et al., 1993). Paroxysms are often associated with lava flows, but their distinctive characteristic is the high energy of the blasts compared to the normal mild explosions at Stromboli. A new eruption started at Stromboli on February 27, 2007, which was associated with a lava effusion until April 2 and a paroxysmal event on March 15. This eruption was the first since the 2002–2003 eruption.

Geochemical investigations have been carried out on the emitted fluids (gas and thermal waters) at Stromboli since 1999, beginning with the identification of preferential degassing zones (Carapezza and Federico, 2000) and the evaluation of dissolved gases exhibiting the main features of a magma origin (Inguaggiato and Rizzo, 2004). Chemical and isotopic evidence of a magma component has been found in the fumarolic gases of the summit area and in some shallow thermal water wells drilled near the northeast coast of the island (Carapezza and Federico, 2000; Finizola et al., 2002, 2003; Inguaggiato and Rizzo, 2004). The focus in subsequent years moved toward the monitoring of parameters that could help to identify relationships between geochemical variations and volcanic activity. A carbon dioxide (CO_2) soil flux survey started in the summit zone in 1999 with the installation of an automated station that recorded the CO_2 soil flux hourly (Carapezza et al., 2002). The discrete long-term monitoring of selected thermal waters and discharged gases started almost contemporarily (Brusca et al., 2004; Carapezza et al., 2004; Capasso et al., 2005a; Federico et al., 2008; Rizzo et al., 2008). This work provided information on the average variability of the investigated parameters during Strombolian activity, which is necessary for identifying geochemical signals that precede eruptions and/or

paroxysmal explosions. The crisis that occurred in 2002 represented the first opportunity to compare the variations recorded during ordinary Strombolian activity with those observed during an unusual and hazardous volcanic condition for Stromboli such as an eruption. Notable increases in the CO_2, hydrogen gas (H_2), and helium (He) dissolved in the thermal waters, together with changes in the compositions of total dissolved carbon (C) and He isotopes, were observed before the eruption onset and before the explosive paroxysm (Carapezza et al., 2004; Capasso et al., 2005a; Federico et al., 2008). Very high CO_2 flux values that had never been observed previously were recorded at the summit station a few weeks before the eruption onset (Brusca et al., 2004). A lowering of thermal water pH was also observed in two wells 1 month before the explosive paroxysm on April 5, 2003 (Carapezza et al., 2004).

The soil temperature has been continuously measured at Stromboli since January 2003. Data acquired during the 2002–2003 eruption from station STR02 (Fig. 1) made it possible to evaluate the potential utility of this parameter, but this was constrained by the sensor position in the soil (Brusca et al., 2004). Therefore, a new measuring point was set up in February 2006, close to station STR02 but at a location more appropriate for reflecting the temperature dynamics. De Gregorio et al. (2007) analyzed data collected between March and October 2006, which provided evidence of several anomalies that were clearly linked to seismic activity and/or the partition ratio of the degassing activity between the fumarolic field and the volcanic conduit.

In this paper, we discuss the variations observed in the geochemical parameters monitored across the 2007 eruption, focusing on a comparison with the anomalies recorded during the 2002 crisis. The magma dynamics during the last two eruptions are also compared.

2. 2007 eruptive activity

On February 27, 2007 (43 months after the 2002 crisis) a new eruption started at Stromboli that was characterized in the first days by a copious lava effusion flowing from a vent that opened at 450 m a.s.l. in the Sciara del Fuoco slope. This lava effusion rapidly reached the sea by two separated flows producing a spectacular vapor cloud as well as modification of the coast morphology at Spiaggia dei Gabbiani. At 2037 hours GMT on March 15 an explosive paroxysm occurred at the craters that involved a gas emission into the atmosphere accompanied by the fallout of bombs and

blocks as well as visible ionization of the gas/ash cloud that formed above the craters. The last recorded paroxysm at Stromboli, which was more energetic, had occurred on April 5, 2003 during the previous eruption. Similar to previous events occurring in the known history of the volcano, the explosion on March 15 was accompanied by the presence of two HK-basaltic components resulting from the sudden ascent of crystal-poor and gas-rich magma through the resident magma, which is degassed and crystal-rich (Métrich et al., 2001, 2005; Landi et al., 2004). The rate of lava effusion decreased after the paroxysm until April 2, when the eruption ended. Following the end of lava effusion, the craters gradually resumed typical Strombolian activity.

3. Sampling and analytical techniques

Thermal waters were collected from four wells (named Fulco, Limoneto, Saibbo, and Zurro; Fig. 1) located near the inhabited center of Stromboli with a sampling frequency of once per month during "normal" Strombolian activity, and up to twice weekly during the 2007 crisis. A nearby fumarole located at Pizzo Sopra La Fossa (PSF) (named SC5; Fig. 1) has also been sampled monthly. All of the collected gas and water samples were analyzed at our INGV-Sezione di Palermo laboratories for their chemical and He- and C-isotope compositions. The sampling and analytical techniques are detailed in Capasso and Inguaggiato (1998), Inguaggiato and Rizzo (2004), and Capasso et al. (2005b). Temperature, pH, conductivity, and Eh were directly measured in the field during water sampling.

CO_2 flux and meteorological parameters (soil temperature and humidity) were measured hourly by an automated station (STR02; Fig. 1) installed in 1999 at PSF. Further details about the technical specifications of the system are available in Carapezza et al. (2002, 2004), Brusca et al. (2004), and Federico et al. (2008).

Soil temperatures were measured within the fumarolic field at depths of 10, 30, and 50 cm by an automated station (SST02) located a few tens of meters east of the top of PSF (Fig. 1). It is based on an onset four-channel data logger connected to three 12-bit digital temperature sensors operating in the range –40 to 100 °C, with a resolution of 0.03 °C and an accuracy of ±0.2 °C. Further details are available in Brusca et al. (2004) and Madonia et al. (2008).

4. Results

4.1 Chemical composition of sampled waters

The chemical and isotopic compositions of the circulating waters at Stromboli have been regularly measured since 2000. The data are listed in Table 1. All groundwater samples show a significant contribution of seawater, with the Na/Cl, SO_4/Cl, and Br/Cl ratios being consistent with those for seawater. In contrast, the Ca/Cl, K/Cl, and Mg/Cl ratios differ significantly from those for seawater, showing Ca and K enrichment. The HCO_3-Cl-SO_4 ternary diagram shown in Fig. 2 indicates that all samples fall between seawater and HCO_3-rich peripheral waters (Grassa et al., 2008).

Seawater contamination is also confirmed by the isotopic compositions of hydrogen and oxygen, which fall between the meteoric endmember defined by Liotta et al. (2006) and the Mediterranean isotopic composition (Grassa et al., 2008).

The chemical and physical parameters did not exhibit significant temporal variations during 2006 and 2007. Fig. 3 shows that the pH values at each site were reasonably constant, in contrast to marked decreases prior to the paroxysm on April 5, 2003 (Carapezza et al., 2004).

4.2 Gases dissolved in water

The content of dissolved oxygen gas (O_2) in water samples was always below the concentration in air-saturated water (ASW; 7 cc/l STP), ranging from 0.1 to 1.5 cc/l STP, while the concentration of nitrogen gas (N_2) ranged from 6 to 16 cc/l STP. Consequently, the N_2/O_2 ratio was always much higher than in ASW, at 1.86. A high concentration of dissolved methane (CH_4) was also observed, ranging from 3×10^{-4} to 1×10^{-2} cc/l STP. The contents of dissolved carbon monoxide (CO) and H_2 ranged from 5.5×10^{-4} to 1.5×10^{-3} and from 6×10^{-4} to 2×10^{-1} cc/l STP, respectively. Also, the dissolved-He concentration was well above the natural value in ASW (4.55×10^{-5} cc/l STP; Inguaggiato and Rizzo, 2004), ranging from 1.5×10^{-4} to 1×10^{-3} cc/l STP. The dissolved CO_2 concentration was highest in the Fulco and Saibbo wells (150–200 cc/l STP) and lowest in the Zurro and Limoneto wells (10–80 cc/l STP). As already observed in previous investigations, gases dissolved in the monitored thermal waters mostly originated from magma with a shallow contribution from the hydrothermal system below sea level (Carapezza and Federico, 2000; Inguaggiato and Rizzo, 2004; Capasso et al., 2005a; Federico et al., 2008; Rizzo et al., 2008). Indeed, since magma and hydrothermal gases can react with the shallow aquifers during their ascent toward the surface, the pristine chemical composition may undergo significant changes that

vary with the solubility in water of the species in the gas mixture and the water volume in which the gas dissolves (Caracausi et al., 2003, 2005; Capasso et al., 2005a). In particular, species with a higher water solubility, such as CO_2, dissolve in water to produce a relative enrichment of less-soluble species such as He, N_2, CO, and CH_4.

To the contrary of what observed during 2002 crisis, long-term monitoring did not reveal appreciable variations in dissolved gases during the 2007 eruption. The variability in dissolved H_2, CO_2, and He is compatible with the gas–water interaction process modelled by Capasso et al. (2005a) during normal activity.

4.3 Carbon isotopes

The $\delta^{13}C$ values of total dissolved inorganic C ($\delta^{13}C_{TDIC}$) of the collected thermal waters were determined. The values were highest at the Fulco, Saibbo, and Limoneto wells (ranging from –0.8‰ to 2.2‰ vs PDB), and lowest values at the Zurro well (ranging from –2.0‰ to 0.6‰ vs PDB). At the SC5 fumarole located in the PSF area the $\delta^{13}C_{CO2}$ value ranged between –1.8‰ and –2.5‰ (vs PDB). All of the data are listed in Table 2.

Starting from $\delta^{13}C_{TDIC}$ values, the isotopic composition of free CO_2 in equilibrium with thermal waters ($\delta^{13}C_{CO2g}$) has been computed (Inguaggiato et al., 2000; Capasso et al., 2005a; Grassa et al., 2006). The calculated $\delta^{13}C_{CO2g}$ values during the investigated period ranged between –1.5‰ and –5.4‰ vs PDB in most of the samples, with it being lower in the Zurro well (–4.8‰ to –7.4‰ vs PDB). According to Capasso et al. (2005a) and Grassa et al. (2008), the lowest values are the result of the isotopic fractionation due to the gas-water interaction process during CO_2 dissolution in the aquifer. Whereas the highest values resemble the C-isotope composition measured in the free gases of the northeast crater, the high-temperature fumarole formed during the 2003 eruption ($\delta^{13}C_{CO2g} \approx$ –1.8‰ vs PDB; Finizola and Sortino, 2003), and of the average values at site SC5 ($\delta^{13}C_{CO2g} \approx$ –2‰), which is the most representative site of the low-temperature permanent fumarolic field in the PSF area.

Such a correspondence in the C-isotope signature has previously been considered clear evidence of a magma origin of CO_2 in the thermal waters of Stromboli (Capasso et al., 2005a; Federico et al., 2008). This hypothesis was verified in the months

preceding the onset of the 2002–2003 eruption and during the eruption itself, based on recorded temporal variations in both the chemical and isotopic compositions of gases dissolved in the thermal waters, particularly in the changes observed in the values of $\delta^{13}C_{CO2g}$ in equilibrium with thermal waters, and in the ratios of dissolved He/CO_2 and $^3He/^4He$ (Capasso et al., 2005a). Such modifications were related to uprising within the conduit of a new and gas-rich batch of magma.

The 2007 eruption was characterized by limited changes in $\delta^{13}C_{CO2g}$ values. During the eruption, and before the March 15 paroxysm, no clear variations related to magma dynamics at depth were recorded at the monitored wells. In contrast, some appreciable variations were evident at fumarole SC5 although the reduced sampling frequency during the eruptive period for safety reasons (Fig. 4). $\delta^{13}C_{CO2}$ increased sharply approximately 2 weeks before the paroxysm, and after the explosion the C isotopes decreased toward the lowest values recorded during the eruptive period. Since April 2007 the values again increased progressively towards the pre-eruptive signature (Fig. 4), almost simultaneously with the resumption of Strombolian activity at the craters.

4.4 Helium isotopes

The $^3He/^4He$ ratios measured in the dissolved gases were in the range 3.9–4.5 Ra (where $Ra=1.39\times10^{-6}$ is the He-isotope ratio in the atmosphere), with the $^4He/^{20}Ne$ ratio being one or two orders of magnitude higher than the value for air ($^4He/^{20}Ne=0.285$; Inguaggiato and Rizzo, 2004). Fumarole SC5 showed $^3He/^4He$ ratios between 2.3 and 3.1 Ra and $^4He/^{20}Ne$ ratios between 0.65 and 1.61. All of the data are listed in Table 2, with the $^3He/^4He$ ratios corrected for air contamination (Rc/Ra) based on the $^4He/^{20}Ne$ ratio measured in each sample (Sano and Wakita, 1985). The determined He-isotope values are very similar to those previously measured by Inguaggiato and Rizzo (2004) and Capasso et al. (2005a), confirming a clear magma contribution to the investigated dissolved gases as well as in the summit area. The variability observed during 2007 is smaller than that observed before the 2002–2003 eruption (Capasso et al., 2005a; Federico et al., 2008).

Nevertheless, temporal variations of Rc/Ra of dissolved gases at all of the sampled sites decreased markedly after November 2006, reaching the lowest values recorded during the eruptive period (Fig. 4). Thereafter the $^3He/^4He$ ratios increased toward

their highest values, which were reached in April 2007 before slowly returning to their pre-eruptive levels. No significant short-time variations were recorded during the eruption, despite the sampling frequency being increased to twice weekly. The trend of the He-isotope ratio observed during the 2007 eruption was similar to that during the 2002–2003 eruption.

The Rc/Ra values at fumarole SC5 decreased progressively from May 2006 to reach their minimum values just after the end of the eruption (Fig. 4). Following the end of the eruption, while seismic signals indicated that the magma in the conduit had risen by about 100 m (INGV report of June 1, 2007), the Rc/Ra values started to increase progressively, returning in August and September 2007 to the pre-eruptive average levels of variability (3 Ra; Fig. 4).

4.5 Carbon dioxide soil degassing

During normal Strombolian activity the daily average CO_2 flux varies between 5000 and 10,000 g $m^{-2}d^{-1}$, which is identical to that measured before the 2002–2003 eruption as well as during the intereruption period between the last two crises (Brusca et al., 2004; Carapezza et al., 2004). As previously observed, a flux anomaly at the surface can result from overpressured gas pockets located at the top of the magma column or from the sudden rising of gas-rich magma toward the surface (Brusca et al., 2004). Particularly, a week before 2002-2003 eruption, the STR02 automatic station recorded CO_2 flux up to 80,000 g $m^{-2}d^{-1}$ (Carapezza et al., 2004). It is worth noting that a similar behaviour has been observed also during last crisis, few days before the onset of the effusive activity. The recorded values (90000 gr $m^{-2}d^{-1}$), never measured during ordinary activity, would confirm that the degassing rate is significantly modified during magma upraise in the upper conduits before an effusive activity.

Soil degassing increased from 4000 to 25,000 g $m^{-2}d^{-1}$ during February–April 2006 (Fig. 5), with this anomaly lasting until the degassing reached very low values of around 2000 g $m^{-2}d^{-1}$ during the second half of April. On February 23, 2007 the CO_2 flux started to increase, reaching 20,000 g $m^{-2}d^{-1}$ on February 26. After the eruption onset, the CO_2 flux reached 90,000 g $m^{-2}d^{-1}$ during the first half of March, a few days before the paroxysmal explosion. Following this major explosion the flux showed a decreasing trend – although with fluctuating values – until the end of the eruption on April 2, 2007. New short-term variations were recorded during the resumption of ordinary Strombolian activity until the end of May.

Since June 2007, the CO_2 flux restarted to vary around the values normally measured during Strombolian activity, between 5000 and 10000 g $m^{-2}d^{-1}$.

4.6 Soil temperature

Soil temperatures recorded at station SST02 are reported in Fig. 6, which shows the running-daily-average temperatures measured at three depths (10, 30, and 50 cm), together with the vertical thermal gradient between 10 and 50 cm expressed in degrees Celsius per meter. The graph reveals two periods characterized by different patterns of variation on a medium-term (months) timescale. The first one, from the beginning of December 2006 to the first half of April 2007, is characterized by pronounced positive and negative anomalies both in temperatures and thermal gradients, with amplitudes of up to 20 °C (temperature) and 30 °C/m (gradient) and durations spanning from hours to weeks. This behavior, as previously described by De Gregorio et al. (2007), accounts for a disturbed regimen characterized by frequent changes in the degassing dynamic from the vents. The onset of this instability period coincides with increasing anomalies in CO_2/SO_2 measured in the plume (Aiuppa et al., this volume), suggesting that both the plume composition and soil degassing are influenced by the migration toward the surface of a new batch of gas-rich magma. This soil thermal regime appeared not to be influenced by the onset and evolution of the eruption, since no significant anomalies were recorded therein.

In contrast, the end of the eruption (April 2) marked the beginning of the second period of thermal activity, which lasted until the end of October. The average soil temperatures increased rapidly by 20 °C, with the vertical thermal gradient decreasing instantaneously at the same time. These anomalies coincided with the presence of pulsating ash emissions from the upper vents, followed by the 100-m uprising of the very long period (VLP) seismic source inside the conduit (INGV report of June 1, 2007). The approach of the degassing source toward ground level, coupled with the closure of the eruptive fracture, probably increased the flux of volatiles through the soil, as revealed by the temperature increase and the reduced vertical gradient (under the same atmospheric conditions, a higher flux is associated with a lower gradient).

Once the volcanic system reached a new equilibrium at the end of October, accompanied by the complete resumption of normal Strombolian activity from the upper vents, the thermal regimen of the soil returned to conditions similar (but not equal) to those during the pre-effusive period; in fact, while the average soil

temperatures were quite similar, the vertical thermal gradient remained about 10 °C/m lower than the values observed at the end of 2006. Therefore, although the limited period of monitoring, the different temperature/gradient ratio observed at PSF after the eruption could have been indicative of permanent changes in the summit fracture field resulting from deep morphological evolution of the Stromboli summit area.

5. Discussion and comparison with the 2002–2003 eruption

The 2007 eruption was characterized by appreciable variations in some of the monitored geochemical parameters, and by minor or even no variations in others. The whole eruptive period can be divided in three main phases (pre-eruptive, syn-eruptive and post-eruptive) where different geochemical variation have been recorded.

Before the onset of effusive activity, only CO_2 flux measured in the soil at PSF displayed a marked increase of the values (Fig. 5). Meanwhile, helium isotopes of dissolved gases displayed a progressive decreasing trend of the values (Fig. 4). This behaviour could be the result of a progressive rise of the magma level in the conduits, that produced an increase of the degassing rate in the crater area and, contemporarily, a lower interaction of magmatic fluids with the basal aquifer.

The water chemistry and the composition of dissolved gases did not display variations suggestive of the approach of a new eruptive phase. Also, the values of C isotopes measured in the dissolved gases were consistent with those during normal activity periods.

During the eruption, the CO_2 flux continued to increase to reach its maximum value (90000 g $m^{-2}d^{-1}$)just before the March 15 paroxysm. Almost simultaneously, $\delta^{13}C_{CO2}$ of the SC5 fumarole increased toward values more typical of magma (Fig. 4) due to degassing of a new magma batch rising toward the surface, which probably fed the explosion that occurred a few days later. In contrast, the $^3He/^4He$ ratio showed only minor variations during the same period (Fig. 4).

Soil temperatures measured at PSF were unstable from the end of 2006 until the end of the eruption. Similar behavior characterized by rapid changes in temperature (Brusca et al., 2004) was observed during the 2002–2003 eruption, with the temperature becoming quite constant once the Strombolian activity resumed at the upper vents. No comparisons are possible with the vertical thermal gradient, because

during the 2002–2003 eruption the soil temperature was measured at a single point at a depth of 30 cm.

After the explosion the CO_2 flux decreased progressively toward the pre-eruptive values (5000–10,000 g $m^{-2}d^{-1}$). The eruption finished within few weeks, after which the CO_2 flux varied widely and reached 25,000 gr $m^{-2}d^{-1}$, while He-isotope ratios in the thermal aquifer reached the highest values recorded during the crisis (Figs. 4 and 5). Also vertical thermal gradient decreased toward average values sensibly lower with respect to the eruptive period. The latter geochemical variations are attributable to a new magma recharge at depth that probably induced the resumption of Strombolian activity. Meanwhile, the vertical thermal gradient decreased toward average values that were appreciably lower than those during the eruption.

Comparison of this new eruption with the 2002–2003 eruption provided the opportunity to verify the variations observed in parameters monitored over the entire period as well as to test previously developed models. From July 2002 until the onset of the 2002–2003 eruption (28th December), peaks of dissolved CO_2, H_2, and He were recorded in all of the thermal wells (Carapezza et al., 2004). Also, the compositions of He and C isotopes measured at the SC5 fumarole increased progressively toward a more magma-like signature (3.3 Ra and ~ –1‰ $\delta^{13}C_{CO2}$, respectively; Capasso et al., 2005a). The CO_2 flux increased sharply to 80,000 g $m^{-2}d^{-1}$ 1 week before the eruption onset. These anomalies have been attributed to an increasing input of deep magma gases, probably due to magma uprising in the volcanic conduits (Carapezza et al., 2004; Capasso et al., 2005a). The most significant variations between the eruption onset and the paroxysm on April 5, 2003 were a decrease in water pH and parallel increases in H_2 and He dissolved in the thermal waters. These variations were attributed to a pressure increase in the hydrothermal aquifer resulting from a large input of deep gases originating from the raising magma (Carapezza et al., 2004).

Overall there were both similarities and differences in the monitored geochemical parameters during the last two eruptions at Stromboli. Some of the variations in dissolved gases composition and C isotopes observed during 2002–2003 were not recorded in 2007. Neither H_2 nor He increased, nor the pH decreased in the thermal waters before the paroxysmal event. The common variations were in the CO_2 flux and $\delta^{13}C_{CO2}$ of fumarole SC5, which exhibited similar behaviors in both eruptions, with comparable values. Particularly, during 2002–2003 the increase in CO_2 flux occurred

few weeks before the onset of effusive activity (80,000 g $m^{-2}d^{-1}$). The CO_2 flux decreased rapidly after the eruption started. In contrast, during 2007 the CO_2 flux increased only a few days before the onset of the effusive activity, with the highest values (90,000 g $m^{-2}d^{-1}$) reached only during the eruption. Finally, it should be noted that the 2007 lava effusion lasted less than 2 months, which is much shorter than the 2002–2003 eruption, and that the March 15 paroxysm was much less energetic than that on April 5, 2003.

Therefore, the small geochemical variations observed during the 2007 eruption indicate that this was of minor importance compared to the 2002–2003 one. However, it still provided the opportunity to confirm the usefulness of monitoring certain geochemical parameters for quantifying the hazardousness of an eruption.

6. Concluding remarks

The 2007 eruption represented a suitable opportunity to validate geochemical monitoring at Stromboli and to compare the recorded variations during previous crisis occurred in 2002. It was characterized by geochemical anomalies that preceded the lava effusion onset and the March 15 paroxysmal explosion and the resumption of Strombolian activity after the end of the eruption, as summarized below:

- CO_2 flux measured at PSF increased markedly during the few days before the eruption onset, peaking just before the paroxysm.
- $\delta^{13}C_{CO2}$ measured in the gases of fumarole SC5 increased sharply before the paroxysmal explosion on March 15, 2007.
- $^3He/^4He$ ratios measured in all of the dissolved gases increased sharply after the end of the eruption during the resumption of Strombolian activity, reaching the highest Rc/Ra values ever measured during the crisis.
- Both the temperatures and the vertical thermal gradient measured in the soil at PSF varied appreciably from November 2006 until the end of the eruption, and stabilized when Strombolian activity resumed.

These variations allowed to recognize a magma upraise in the upper conduits, which probably fed the eruption onset, that was probably accompanied by the rapid ascent of a volatile-rich magma before the paroxysm. After the end of effusive phases, a new magma recharge was reasonably recognized, feeding the resumption of Strombolian activity. The comparison with the geochemical variations observed during the 2002–

2003 eruption revealed that the recent eruption was preceded by minor geochemical signals that occurred during the eruption. The basal hydrothermal system appeared to be less involved, probably due to the interaction of only a small amount of magma gases with the shallow aquifer. These observations are consistent with the volcanological evidence of a very short eruption time span and low paroxysmal explosive energy relative to the 2002–2003 crisis.

Finally, the most important result achieved during 2007 eruption is represented by the confirm of CO_2 flux measurements in the soil at PSF that showed an almost identical variation preceding both 2002 and 2007 crisis, and thus may now represent a valid short-term warning (from few days to few weeks) of effusive activity approaching at Stromboli.

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Captions

Table 1 – Chemical analyses of monitored thermal waters. Data are expressed in the following units: mEq/l; Eh, mV; conductivity, mS; and temperature, °C. n.d.=not detected.

Table 2 – He isotopes measured in all of the dissolved gases as well as He- and C-isotope compositions of the SC5 fumarole.

Figure 1 – Sketch map of Stromboli (Aeolian Islands, Italy; modified from Rizzo et al., 2008) showing the sampling sites. Circles on the northeast part of the volcano indicate the investigated thermal wells. The square indicates the fumarole sampled at the top of the volcano. Adjacent to this fumarole are the automated stations for monitoring the soil CO_2 flux (STR02) and temperature (SST02).

Figure 2 – HCO_3-Cl-SO_4 ternary diagram for classifying water samples. All samples fall between seawater and HCO_3-rich peripheral waters.

Figure 3 – Long-term monitoring of water pH in all of the investigated wells. The periods of the eruption and the paroxysm are indicated by the black segment and the vertical red line, respectively.

Figure 4 – Temporal variations of $^3He/^4He$ ratios expressed as Rc/Ra at all of the sampling sites, as well as of $\delta^{13}C$ (CO_2) of fumarole SC5. The symbols and eruptive events are as in Fig. 3. Left and right axes relate to the thermal wells and fumarole SC5, respectively. Sampling of SC5 was interrupted for safety reasons between the onset of the eruption and the end of dangerous conditions.

Figure 5 – Temporal variations of CO_2 flux (expressed in g m^{-2} d^{-1}). Data are running averages across 24 hourly points. Vertical black lines represent the eruption onset and end, while the vertical red line is as in Figs. 3 and 4.

Figure 6 – From bottom to top, daily running averages of the vertical thermal gradient between depths of 10 and 50 cm, and of the soil temperature at depths of 10, 30, and 50 cm measured at station SST02 between November 2006 (installation date) and December 2007.